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The XMM-Newton view of the radio-quiet neutron star 1E 1207.4–5209

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Abstract. We have observed the radio-quiet X-ray pulsar 1E 1207.4–5209 with the high throughput EPIC cameras onboard XMM-Newton. The spectrum of this peculiar source is characterized by two broad absorption features which present significant substructures and show a clear phase-dependence. We believe that these features represent a strong evidence for the presence of a magnetized atmosphere containing heavy elements.

1. Introduction

More than thirty years after the discovery of radio pulsars, the problem of understanding the properties of condensed matter in the interior of Neutron Stars (NSs) has remained largely unsolved. A promising way to obtain constraints on the equation of state of NSs is represented by the study of thermal radiation (peaking at X-ray energies) from their surfaces. The observed spectra are expected to show, as a characteristic signature of radiative transfer effects induced by the atmosphere surrounding the NS, several absorption features. These, if correctly deciphered, could unveil the NS physics. However, no such features were ever detected in the X-ray spectrum of a neutron star until recently, when Chandra and XMM-Newton observed the radio-quiet NS 1E 1207.4–5209.

This peculiar source (Bignami et al.1992; Mereghetti et al.1996), located close to the center of the high galactic latitude ($b \sim 10°$) supernova remnant G296.5+10.0, was securely identified as a NS when fast pulsations (P$\sim$424 ms) were detected by Chandra (Zavlin et al.2000); a second Chandra observation led to the discovery of two broad absorption features in its X-ray spectrum (Sanwal et al. 2002).

Here we report on an XMM-Newton observation (30 ksec) performed on 2001, December. The high throughput of the EPIC instrument allowed for a deeper study of the phenomenology of 1E 1207.4–5209. See Mereghetti et al.(2002) for more details.

2. The XMM/EPIC results

We measured a period of 424.13084±0.00046 ms, implying a surprisingly low value of the period derivative, $\dot{P}$=(1.98±0.83)×10^{-14} s s^{-1}, in agreement with (but more accurate than) the Chandra estimate (Pavlov et al. 2002).

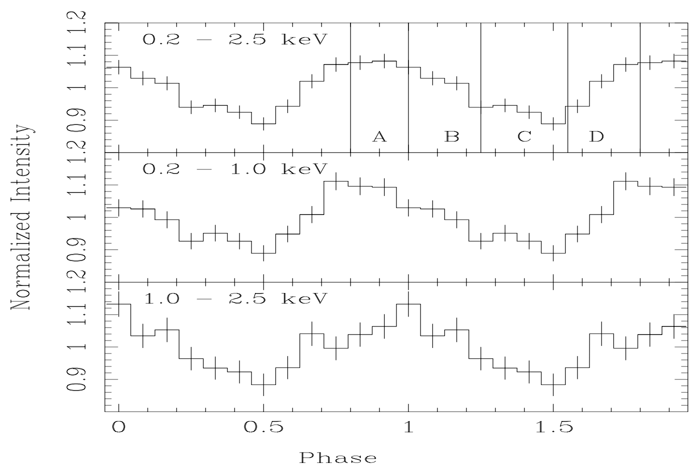

Figure 1. Energy-resolved light curves of 1E 1207.4–5209.

The pulse shape does not present any significant energy dependence (see Fig.1), at variance with the findings of Pavlov et al.(2002), who reported some evidence for a phase shift of 0.4÷0.6 between the energy bands 0.3-1.0 and 1.0-1.7 keV. If the latter result is confirmed, it might imply a time-variable light curve.

The spectrum of 1E 1207.4-5209 is characterized by two broad absorption features at 0.7 and 1.4 keV (Sanwal et al.2002). Figure 2 (left) presents the results of the analysis of the EPIC pn spectrum by showing the residuals obtained with different models.

- Panel 1: a simple blackbody fits is clearly inadequate
- Panel 2: the weakly-magnetized Hydrogen atmosphere model by Zavlin et al.(1996), although possibly inappropriate to the case of 1E 1207.4-5209 (inferred B$\sim 3 \times 10^{12}$ G), gives residuals very similar to the blackbody fit.
- Panel 3: models of NS atmospheres with solar abundance (Gänsicke et al.2002) give unacceptable fits, since the predicted features are much narrower than the observed ones. The same is true for Fe composition.
- Panel 4: acceptable fits required the inclusion of two absorption lines, that we modeled for simplicity as gaussian lines: here we give the residuals to a blackbody+lines fit.

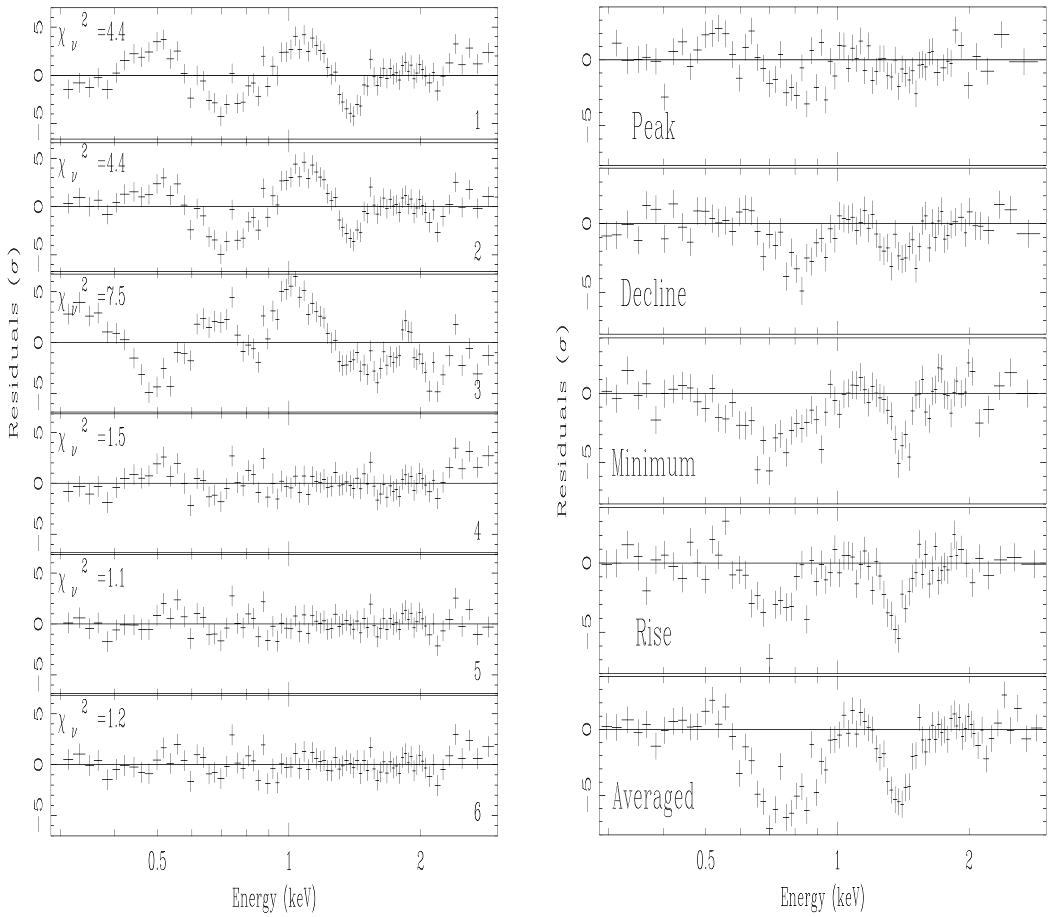

Figure 2. (left) Results of phase-averaged spectroscopy; (right) results of phase-resolved spectroscopy. See text for details.

- Panel 5: a further improvement was obtained by adding a power law: we believe that this reflects the shortcomings of other models alone to reproduce the low-energy part of this complex spectrum, rather than being evidence for a distinct non-thermal component.
- Panel 6: for completeness, the residuals to an hydrogen atmosphere+lines fit are shown here.

The plots in panels 4÷6 show that the broad feature at 0.7 keV is not well described by a single gaussian line. Significant substructures suggest that the feature may be due to the blending of several narrower lines.

The EPIC pn data were divided in four subsets corresponding to the phase intervals shown in Fig.1. The resulting spectra provide striking evidence of pulse-phase variations of the spectral features. This is clearly shown in Fig.2 (right): we have fitted a blackbody+power law model after excluding the energy bands corresponding to the features. The residuals on the overall energy range show that the line at 1.4 keV is more pronounced during the minimum and the rising part of the pulse profile, while it is almost unvisible during the pulse peak. The feature below 1 keV presents a significant variation in shape, possibly due to different contributions of several narrower lines during the various phase intervals.

3. Conclusions

Our XMM-EPIC observation of 1E 1207.4-5209 has shown new, crucial details of the phenomenology of this puzzling source.

The timing analysis yielded a very low value for the period derivative. The resulting characteristic age, $\tau_c = (340 \pm 140)$ kyrs, turns out to be much higher than the age of the host supernova remnant,$\tau \sim 10$ kyears. This discrepancy can be settled by supposing that the NS was born with a spin period very similar to the observed one.

Most important, the spectral analysis has revealed that the absorption features have significant substructure and are phase-dependent. This strongly supports an interpretation in terms of atomic transitions in the neutron star atmosphere, different regions with different physical conditions being responsible for the emission visible at different phases. The actual chemical composition of the atmosphere is an open problem: Sanwal et al.(2002) proposed once ionized Helium in a superstrong magnetic field ($> 10^{14}$ G, hardly conciliable with the value inferred from the pulsar spin parameters); we prefer an interpretation in terms of heavier elements in a more conventional ($\sim 10^{12}$ G) magnetic field. Indeed, Hailey & Mori (2002) suggested that the lines could be produced by He-like Oxigen or Neon, predicting the presence of substructures in the broad features.

A second, very deep (250 ksec) XMM observation of 1E 1207.4-5209 has now been successfully performed (August 2002). The new data will allow for a more detailed analysis of phase-resolved spectra. This will yield important and maybe conclusive information on the atmosphere composition, hopefully providing firm constraints on the other neutron star parameters.

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